



Competency 2.3 Personnel shall demonstrate knowledge of basic radiation detection methods and principles.

1. SUPPORTING KNOWLEDGE AND/OR SKILLS

- a. Describe the type of radiation detected and the method of radiation detection of the following radiation detection instruments:
 - Gas-Filled Detector
 - Proportional Counter
 - Ionization Chamber
 - Scintillation Detector
 - Geiger-Müller Detector
- b. Describe the proper use, function, and radiation detected by different types of Thermoluminescent Dosimeters and Pocket Ion Chambers.
- c. State the purpose and function of the following radiation monitoring systems:
 - Criticality
 - Area
 - Process
 - Airborne



2. SUMMARY

This competency addresses various types of portable radiation survey instrumentation, radiation detection devices, and monitoring systems. The first category, portable survey instrumentation, consists of four basic types: ionization chambers, Geiger-Müller (G-M) detectors, proportional counters, and scintillation detectors. The first three types are generally categorized as gas-filled detectors since they all employ a fill gas of some type for proper operation. The latter category utilizes a solid medium for the detection of ionizing radiation. Examples of each of these types will be described along with some of their uses and characteristics.

Survey instruments are used for a variety of purposes. Among these are:

- Monitoring contamination levels on equipment and personnel
- Locating lost or hidden sources
- Surveying installations for radiation hazards
- Evaluating the need for posting radiation warning signs
- Predicting the possible exposure in an area and determining the necessity of wearing personnel monitoring devices
- Performing leak tests on radioactive sources

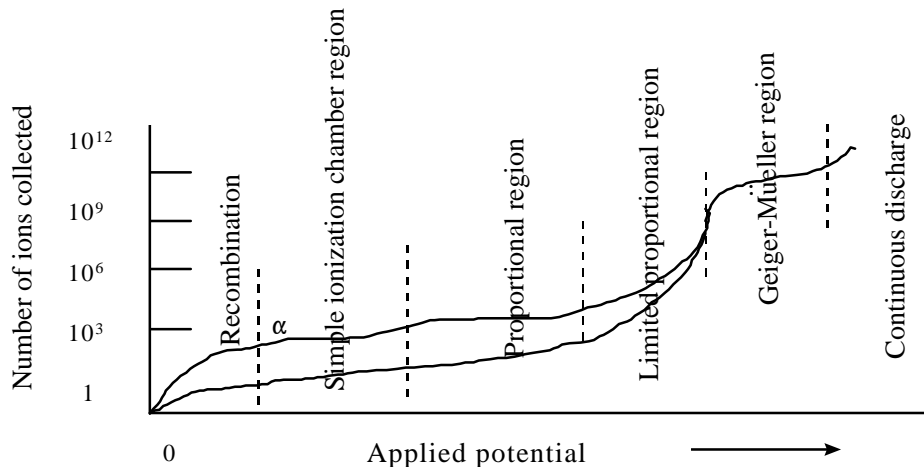
Gas-Filled Detectors

Gas-filled detectors can be designed to detect any of the commonly encountered types of ionizing radiation (alpha, beta, gamma, x-ray, or neutron). In general, these detectors contain a variety of different gases that are either sealed inside a metallic chamber (typically a cylinder) or open to the atmosphere. A wire occupies the center of the chamber. High voltage is supplied to the detector, resulting in the production of an electric field. Radiation interacting within the sensitive volume of the detector is of sufficient energy to "strip" or eject one or more electrons from neutral gas molecules, a process known as gas ionization. The ionization process results in the formation of ion pairs: negatively charged electrons and positively charged gas molecules. The electrons are collected at the central wire either as an electrical pulse (pulse mode) or a current (current mode).

The general gas curve (also referred to as the six-region curve) is a theoretical curve that indicates the general region of operation for gas-filled detectors. The curve appears on the following page.



General Gas Curve



Relation of pulse size to potential gradient in an ionization chamber

In a gas-filled detector, the number of ion pairs measured by the detector per ionizing radiation event is dependent upon the voltage applied to the detector. At low voltages, an ionizing radiation event may not be detected because the ions recombine before reaching the collecting electrode. This area of the general gas curve is referred to as the recombination region.

As the applied voltage increases, ion pairs attain greater kinetic energies and recombination does not occur. This is known as the ionization chamber region. When the voltage is increased above the ionization chamber region, the ions have enough kinetic energy to create new ion pairs after collisions with gas molecules. These new ions are referred to as secondary ions; the number of secondary ions increases proportionally with voltage and with the initial (primary) ions created by the radiation event. This is known as the proportional region. The ratio of the number of secondary ions to primary ions is referred to as the gas amplification factor. As the voltage is further increased, the detector operates in the limited proportional region, a region that is not utilized for radiation detection purposes. Region 5 of the general gas curve is known as the G-M region; any initial ionization event in the detector results in a geiger discharge where the central wire becomes completely saturated with electrons. Region 6 is known as continuous discharge-- a region in which certain G-M detectors are rendered inoperative within a short period of time.

From a practical perspective, gas-filled detectors operate in one of three regions: ionization chamber, proportional, or G-M. Each instrument type is designed to operate in one of these regions through the proper choice of construction materials, anode diameters, fill gas, gas-filling pressures, high voltage, etc.



Ionization Chambers

Ionization chambers operate in the ionization chamber region (region 2) of the general gas curve. Characteristics associated with these detectors include:

- Operate in current mode
- Air is typically used as fill gas
- Gas amplification (multiplication) not required for operation
- Fairly rugged devices
- Short warm-up times (<1 minute)
- Primarily designed to measure x-ray and gamma ray radiations
- Typical readout in units of milliroentgen per hour (mR/hr) or roentgens per hour (R/hr)
- Slow response (relatively insensitive devices)
- Ideal for exposure rate measurements; can measure very high radiation levels with virtually no dead time
- Flat energy response above 100 kiloelectron volts (keV)
- Sensitive to temperature, pressure, and humidity conditions
- Detector can "leak" current, most designs require a "zero" strip adjustment
- Can detect/measure alpha and beta radiations with appropriate calibration factors and/or instrument design.

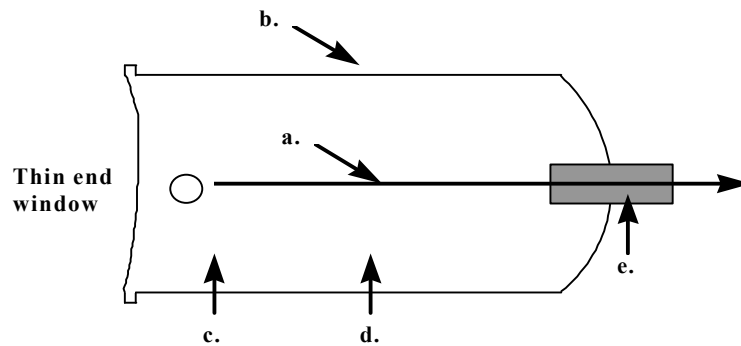
Geiger-Müller Detectors

G-M detectors are widely used instruments for the detection of ionizing radiation. These detectors, often referred to as Geiger or G-M counters, are one of the oldest radiation detection devices in existence. A G-M detector, as previously noted, is a gas-filled detector operated in the G-M region (region 5) of the general gas curve.

All Geiger detectors share certain design features. The diagram below depicts an "end window" G-M tube with key components labeled. A brief description of each follows.



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- a. Anode** - A positively charged central wire, typically composed of tungsten, with a diameter on the order of 0.003 to 0.004 inches. Tungsten is favored for its strength and uniformity. The anode is typically a straight wire, but wire loop anodes are found in other designs (e.g., "pancake" detectors).
- b. Cathode** - The outer envelope and conducting surface, negatively charged with respect to the anode. It is usually composed of metal (steel or nickel) and, on occasion, glass that requires an inner conductive coating.
- c. Fill Gas** - A noble gas that occupies 90 to 95% of the active volume of the detector. The noble gas is typically helium, neon, or argon.
- d. Quench Gas** - A gas occupying 5 to 10% of the detector volume. The quench gas functions to prevent the formation of spurious pulses.
- e. Insulator** - Prevents arcing inside the detector.

High voltage applied to the detector allows the collection of ion pairs--electrons are collected at the anode while positively charged gas molecules migrate to the cathode. The detector usually operates below atmospheric pressure.

To understand the operation of a G-M counter, it might be useful to consider the steps involved in the production of the geiger discharge that creates pulses of uniform size.

Step 1: Ionizing radiation enters the detector and strips an electron from a neutral fill gas molecule, creating an ion pair.



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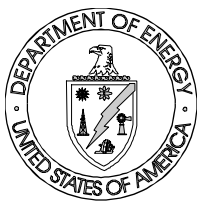
- Step 2: Due to the high electric field (high voltage), the "free" electron accelerates toward the anode. As it does so, it acquires sufficient energy to create secondary ionizations. These secondary ionizations serve to dramatically amplify the number of electrons arriving at the anode. This initial amplification is called the Townsend avalanche (the avalanche created by a single original electron).
- Step 3: A series of avalanches follows in rapid succession, propagated by photon emission created by the excitation and subsequent de-excitation of electrons that were not ionized. The wavelength of these photons is in the visible or ultraviolet region.
- Step 4: The anode becomes completely enveloped with electrons indicating a geiger discharge has occurred.

The geiger discharge is formed in approximately one microsecond (μsec) following the initial ionization in the detector. Because the same number of avalanches (statistically speaking) are created each time during this process, the output pulse represents the same amount of collected charge. Therefore, the pulse's height or amplitude remains constant and no energy discrimination is possible.

One of the most significant disadvantages associated with G-M counters is their so-called "dead" time, a period in which the tube does not respond to radiation. It is caused by the slow movement of the positive ions away from the anode; the electric field intensity is too low to produce a geiger discharge.

There are three principal types of G-M counters that are routinely used in health physics:

- end window
- side wall
- pancake



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Principal Type	Description
End Window	The radiation enters the sensitive volume of the detector by passing through a very thin mica window (thinner than a piece of paper) attached to the end of the detector. The window may be protected by a mesh screen. Thin end windows are capable of detecting alpha, beta, and gamma radiations under the appropriate conditions and with proper survey techniques.
Side Wall	This detector has a sliding sleeve that opens and closes from the side. Higher energy beta particles (~300 keV and above) and gamma rays can be detected with the window open; closing the window eliminates the beta contribution and that of lower energy photons.
Pancake	A pancake G-M is similar to the end window in that a very thin mica covering is used. Its design offers a greater detection area than the end window probe in addition to having the same capability of detecting a variety of commonly encountered radiations.

G-M detectors have a wide variety of uses. As a general comment, however, it must be mentioned that because all pulses from a G-M counter are of the same amplitude, no energy discrimination is possible (no spectroscopy). G-M counters do not respond with equal count rates to equal exposures rates from photons of differing energies. Therefore, they are best suited to count rate determinations rather than measurements of exposure, exposure rate, activity, etc. Geiger counters are detection instruments first and foremost. That having been said, some specific applications now follow.

- Contamination Surveys - Fairly rapid monitoring of personnel (hands, clothing, etc.), equipment (tools, etc.), and laboratory surfaces (benches, tabletops, hoods, etc.) can be accomplished using a variety of G-M detectors. When surveying for soft beta emitters, such as carbon-14 (C-14), sulfur-35 (S-35), calcium-45 (Ca-45), and phosphorus-32 (P-32), a thin end window or pancake detector would be required. Higher energy beta and gamma emitters could be detected with end window, pancake, and side wall G-M detectors. These surveys and the detectors involved can be utilized in both laboratory and field applications.
- Leak Testing - Leak testing is a procedure designed to determine whether any removable activity above a specified value is present on the outer surfaces of a sealed source. A smear is taken on the outer surface and counted in a G-M detector. The resulting count rate, with background subtracted, is a measure of the removable activity. If the efficiency of the detector is known, count rates can be converted into disintegration rates for comparison with the guideline value. This procedure is often followed for industrial radiography sources where the opening (port) that the source passes through is smeared with a Q-tip and counted as described above.



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- Accident Dosimetry - Geiger counters can be used for estimating the neutron dose from the activation of sodium-23 (Na-23) to Na-24 in the blood. A "pancake" probe, for example, is placed either against the abdomen of the individual as he/she bends over or under the armpit. Any measurable increase in the count rate (over background) can be an indication of a significant neutron dose. This procedure is referred to as the quick sort method because it can rapidly screen individuals following an accident. The procedure is based on detecting gamma rays emitted from the decay of Na-24.
- Exposure Rate Measurements - In general, measurements of exposure rates can cautiously be performed under two circumstances: when 1) the accuracy of the results is not a crucial concern and 2) the instrument is calibrated for the same energy that will be encountered in the field or laboratory.

A variety of G-M counters can be used for exposure rate measurements (keeping in mind the caveats noted above). These include the typically encountered end window, side wall, and pancake designs. In addition, modified detectors are also available. For example, an energy-compensated side wall G-M tube consists of a rubber sleeve that slides over the tube to flatten the photoelectric response of the detector. Depending on the probe design, exposure rates of up to several R/hr can be measured. A telescoping detector is also available; in this design, a probe containing two halogen-quenched G-M tubes can be extended up to approximately 14 feet from the user and the readout device. Exposure rates of up to 1,000 R/hr can be recorded while the surveyor's dose is dramatically reduced by utilizing distance. This particular G-M detector has practical applications in several areas: radioactive waste surveys, monitoring irradiated fuel storage and transport, monitoring the removal of irradiated samples from reactors, reducing exposure to personnel when locating and evaluating radioactive sources of unknown strength, and emergency radiation accidents.

Typical advantages and disadvantages of GM detectors follow.

Advantages:

- Fairly reliable
- Ease of operation
- Wide variety of shapes and sizes
- Relatively inexpensive
- Highly sensitive (one ion pair can produce a discharge)
- Large output pulses (>1/4 volt to several volts)



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- No external amplification normally required due to large amplification factors inherent in the operation of the detector (minimal electronics)
- Used in field and laboratory settings
- Detect a wide variety of radiations including alpha, beta (soft and hard), x-ray, gamma, and cosmic (high energy gammas)
- Choice of proper operating voltage allows for reproducible results even if the voltage varies
- Excellent for low-level counting rate surveys including personnel and equipment monitoring, leak tests, and as a quick screening method in accident situations
- Halogen tubes have technically infinite lifetimes
- Exposure rate measurements possible under proper conditions

Disadvantages:

- No energy discrimination (spectroscopy is not possible)
- Principally detection, not measurement, devices
- Quenching required to eliminate multiple pulsing
- Worst resolving times of any gas-filled detector
- Slope of the plateau must be kept reasonably flat for reproducible results
- Organic tubes have limited lifetimes
- Self-absorption in the counter wall and window is possible for alpha and beta radiations
- Efficiency is quite poor for gamma rays (approximately 1%)
- Without antisaturation circuits, detector can saturate in high radiation fields and read lower than the true value or even "zero"

Proportional Counters

Proportional counters are extremely versatile instruments used for the detection of ionizing radiation. They share certain design features. Various key components are described below.

Anode - Typically composed of tungsten, with a diameter of approximately 0.001 inches. The anode either takes the form of a loop or straight wire. The nature of gas amplification in a proportional counter requires an extremely uniform central wire.



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Cathode - The outer envelope and conducting surface, negatively charged with respect to the anode, and usually composed of steel.

Fill Gas - The gas that occupies the sensitive volume of the detector. It may be an inert gas (argon, krypton, xenon) or a hydrocarbon (methane, ethylene). Other gases are used depending on the application. A very common proportional gas, known as P-10, consists of a mixture of 90% argon and 10% methane. The methane serves as a quenching agent.

Insulator - Prevents arcing inside the detector.

A proportional counter operates in the proportional region (region 3) of the general gas curve where the applied high voltage is sufficiently high to create secondary ionizations. In contrast to G-M counters, where all pulses are of the same amplitude, the size of the pulse in a proportional counter is proportional to the initial number of ion pairs produced in the detector volume.

When ionizing radiation enters the sensitive volume of a proportional counter, ion pairs are created. The free electrons that are initially produced accelerate toward the anode; secondary ionizations result from the potential applied to the detector. This is known as gas amplification. The number of electrons that arrive at the anode constitute an avalanche (Townsend avalanche). In these respects, proportional counters are similar to G-M counters. Here the similarities end, however. G-M counters operate with amplification factors on the order of one billion (10^9); a series of avalanches eventually envelopes the entire anode, producing pulses of uniform size. In contrast, proportional counters rely on much lower amplification; values in the one thousand (10^3) to one hundred thousand (10^5) range are typical. The anode does not become saturated with electrons and the pulse height is proportional to the initial number of electrons produced in the gas. Energy discrimination with the ability to distinguish radiations becomes possible.

Proportional counters are known for their short dead times. These counters have the capability to distinguish two pulses (two separate ionizing events) in a short period of time. Since each avalanche is restricted to a short section of the anode, unlike G-M counters, the counter can clear this avalanche and respond to a new ionizing event in a time frame approximating 0.5 to 5 μsec . This is a decided advantage when high counting rates are involved.

A variety of counters operating in the proportional mode exist for routine and specialized applications. Two of the more common examples are:

- **Air Proportional** - These counters respond only to alpha radiation. Alpha particles enter the detector through a thin window of aluminized mylar. The fill gas is air instead of a noble gas. These lightweight, portable counters are useful for contamination surveys, but must be used with caution in areas of high humidity. For this reason, they are most often encountered in the western half of the United States, where humidities are lower and the response of the detector is not adversely affected.



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- Gas Flow Proportional (field use) - These portable instruments respond to both alpha and beta radiation through the appropriate selection of operating voltage. In one design, the fill gas (often liquid propane) is contained in a small canister inside the instrument housing; gas is fed from the canister through a teflon tube housed inside an electrical cable to the probe. The canister is usually replaced every four to six hours. Other designs utilize larger cylinders as the source of the counting gas (often P-10). The counter can be purged of air and operated as a stand-alone unit if desired.
- Gas Flow Proportional (laboratory use) - Proportional counters in a laboratory setting often require the use of large gas cylinders and lead shielding (to reduce background), which limits their portability. The counter can be configured to allow radiation from the source to directly interact with the fill gas, eliminating the need for a thin entrance window. The design is appropriately called a windowless gas flow counter. Thin entrance windows can also be used; however, corrections for self-absorption must be applied. The counting geometry is such that in a hemispherical arrangement all the radiation emitted from the surface of the source or sample can be detected. This is known as 2π (pi) geometry, which infers counting efficiencies of 50%. A 4π geometry is also possible whereby the source backing is thin compared with the range of the radiation. Radiations can then be detected from all directions, with efficiencies approaching 100%.

Common applications associated with proportional counters include:

- Contamination Surveys - Detection of alpha and beta radiations can be performed with portable instruments (air proportional and gas flow counters). Large floor surfaces, for example, can be rapidly screened for contamination using a portable, multiwire anode gas-flow counter with a 600 cm² effective surface area. The floor monitor can be moved over the area of interest to quickly identify contaminated locations. Follow-up surface contamination measurements can then be performed with other field proportional counters or another instrument of choice.
- Neutron Detection - Detection of slow neutrons can be accomplished using pulse height discrimination. In a very common reaction, boron trifluoride gas interacts with slow neutrons to produce alpha particles. The alphas are counted while gamma rays are rejected based on their respective pulse heights. The neutrons are detected indirectly by the formation of alpha particles. Other proportional gases are routinely used to accomplish the same objective. The counter can also be modified through the use of moderators to detect fast neutrons.



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- Assay of Alpha, Beta, and X-ray Sources - Proportional counters can be used to assay (measure) source activities under the proper conditions. The thickness of the source and source backing must be considered in terms of absorption, especially for alpha and beta radiations.

Typical advantages and disadvantages of proportional counters follow.

Advantages:

- Versatile instruments (wide variety of applications)
- Variety of shapes and sizes available
- Highly sensitive (counter can respond to the formation of one ion pair)
- Size of pulse proportional to initial number of ion pairs
- Can detect (directly or indirectly) a variety of radiations: alpha, beta, gamma, x-ray, and neutrons
- Can distinguish radiations (alpha, beta, etc.) based on pulse height discrimination
- Energy discrimination (spectroscopy)
- Ability to count at much higher rates, relative to G-M counter, because of excellent resolving times (0.5 to 5 μsec)
- Not only detection, but measurements of dose and dose equivalent possible
- Used in field and laboratory setting

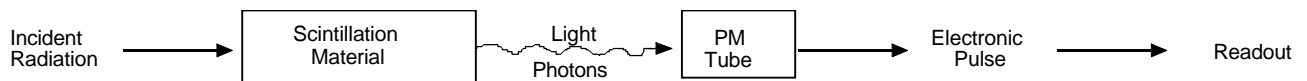
Disadvantages:

- Stable high voltage required due to nature of gas amplification
- External amplification (preamplifiers, amplifiers) required to produce pulse of sufficient size for detection
- Generally more expensive than G-M counters
- Proper operation requires more attention on the part of the user
- Instruments tend to be "finicky" (i.e., more attention to maintenance is required [not as reliable as geiger counters]).
- Susceptible to environmental conditions (heat, humidity)
- Self-absorption possible in counters employing entrance windows
- Efficiencies are poor for higher energy x-rays and gamma rays



Scintillation Detectors

In contrast to gas-filled detectors (G-M counters, proportional counters, and ionization chambers), a solid medium can be used as the sensitive volume for the detection of ionizing radiation. The use of a solid in this regard can be found in the case of inorganic (noncarbon) scintillation detectors. The scintillation mechanism (described below) was the first method ever used to detect ionizing radiation having been observed by Roentgen as a fluorescence on a screen during his discovery of x-rays. Rutherford's classical scattering experiments with alpha particles also relied on the scintillation process. Many years later, solid scintillators of various types are widely used for the detection of alpha (α^{++}), beta (β^{-}), x-ray (x), gamma ray (γ), neutron (n), and proton (p^{+}) radiations.



The process by which an electrical pulse is generated consists of four main steps:

- Step 1: Interaction of ionizing radiation with the detector producing electron-hole pairs.
- Step 2: Conversion of the energy deposited in the detector produced into a proportional amount of light.
- Step 3: Conversion of the light emitted by the scintillator into photoelectrons at the photocathode of the photomultiplier tube.
- Step 4: Multiplication of the initial number of photoelectrons into a measurable electrical pulse.

The end result is that an electrical pulse is produced whose amplitude is proportional to the energy deposited in the scintillator by the incident radiation.

The following are examples of two commonly encountered inorganic scintillation detectors.

- Sodium Iodide (NaI) - An alkali halide whose discovery and use dates back to the late 1940s. Thallium (Tl) is added in trace amounts as an activator or "wavelength shifter" in order to produce a wavelength of light preferably in the visible region or a wavelength that closely matches the spectral sensitivity of a photomultiplier tube.



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NaI(Tl) has several notable characteristics. The crystal exhibits an excellent light yield and can be machined into a variety of shapes and sizes. Negative characteristics include its fragility (sensitivity to thermal and mechanical shocks), and its hygroscopicity (propensity for absorbing moisture). Also, the scintillation photon is not always emitted as a prompt fluorescence--a disadvantage for applications involving high counting rates. Lastly, NaI detectors are energy-dependent devices and should typically be calibrated to the energy of interest.

- Zinc Sulfide (ZnS) - Lord Rutherford used ZnS to visually observe alpha particle interactions during his early scattering experiments. This inorganic scintillator has an efficiency comparable to NaI(Tl). Unlike sodium iodide, however, zinc sulfide is available only as a crystalline powder with density thicknesses on the order of 25 mg/cm². Silver is used as the doping agent. Its use is limited to thin films or screens for alpha and other heavy ion (protons, for example) detection. In practice, ionizing radiation (typically alpha) penetrates a thin aluminized mylar covering prior to interacting with the ZnS(Ag) powder. This covering can be easily punctured, resulting in pinhole (or worse) leaks. The detector will then respond to extraneous light sources.

Scintillation detectors are used for a variety of practical applications. These include:

- Gamma spectroscopy: NaI detectors have been the workhorse in this area for a number of years. While the resolution of these detectors compared with germanium detectors is poor, it is balanced by their inherent high efficiencies.
- Environmental: Applications here include: 1) the finding of elevated gamma radiation levels (anomalies) along roadways, fence lines, etc.; 2) aerial radiological "fly-overs" of an area for the purpose of mapping the radionuclide distribution of all gamma emitters detectable from the surface, with results extrapolated to one meter above the surface and reported in units of cps or $\mu\text{R/hr}$; 3) continuous readout devices that send updated environmental exposure rates back to a central location on a frequent basis (every 15 minutes or so); and 4) grid point measurements and walk-over surface scans.

Examples of scintillation detectors used in the environment include:

- Micro-R (μR) meters - The scintillator is positioned inside the instrument casing. The instrument is designed to read out in units of $\mu\text{R/hr}$.
- "FIDLER" detectors (Field Instrument for the Detection of Low Energy Radiations) - This detector consists of a 5-inch by 0.06-inch wafer-thin NaI crystal used in the field when low energy photons are the radiations of concern. Radionuclides of interest include americium-241 (Am-241), depleted uranium, and plutonium-239 (Pu-239).
- NaI probes containing crystals of various sizes (1-inch by 1-inch, 2-inches by 2-inches, etc.) simply attached to a ratemeter or scaler and held by the operator using a rope. The probe is therefore found outside the instrument case (unlike the μR meter).



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- Nuclear Medicine: NaI detectors are used in Anger Cameras, well counters, rectilinear scanners (now practically obsolete), organ uptake probes and whole body counters. Both in-vivo and in-vitro applications are involved as are specialized techniques such as SPECT (Single Photon Emission Computerized Tomography).
- Reactors: These detectors are used as liquid waste water monitors and for surveys of low-level radioactive materials (trash, clothing, etc.).
- Whole-Body Counting: Detectors, usually measuring 4-inches by 5-inches, are often used to detect gamma radiation emitted from the body.
- Geological Surveys: Sodium iodide detectors are used for oil-well logging and aerial surveys.

Liquid Scintillation Counting

Liquid scintillation counting (LSC) is a specialized/sophisticated laboratory technique for assaying (quantifying) principally low energy beta emitters. It is not ordinarily used for identification of radionuclides unless the spectrum is simple in nature. The basic theory behind LSC is that a radioactive sample is dissolved in a solution that fluoresces (emits light energy) when the solution absorbs radiation energy. The light is converted into electronic pulses, which are proportional to the energy dissipated by the radiation.

LSC is an excellent choice when the objective is assaying low energy "pure" beta emitters, such as tritium (H-3), C-14, S-35, and Ca-45, simply because these emitters are difficult to detect by other techniques. Higher energy beta emitters such as P-32 can also be assayed by this method. In recent years, the use of LSC for counting and quantifying alpha emitters has markedly increased. Gamma emitters, however, are not normally assayed by this technique.

LSC has several advantages including the lack of sample self-absorption or backscatter, good geometry, and good efficiencies (up to 100%). Applications include counting and analyzing water and urine bioassay samples, air filters, vegetation, animal tissue, and waste material. Site screening and cleanup associated with DOE remediation projects can be expedited. Alpha and beta counting can now be done simultaneously. Principal disadvantages have historically included the problems of luminescence (more light emitted than desired) and quenching (loss of the light signal).

External Dosimetry and Personnel Monitoring

An individual can receive a dose from either an internal or external source of radiation. Doses from internal sources can be evaluated by performing bioassay procedures, whole-body counting, or calculating an intake based on known air concentrations. Doses from external sources, on the other hand, can be evaluated by calculating the length of time spent in a radiation field of known intensity



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through radiation monitoring or using personnel dosimeters. The use of personnel dosimeters is one of the most important aspects of an external dosimetry and personnel monitoring program--a program designed to not only detect, but measure (dosimetry) and evaluate individual exposures to ionizing radiation.

DOE issued a series of implementation guides (IGs) to assist in the implementation of 10 CFR 835. In particular, the IG entitled *External Dosimetry Program* (G-10 CFR 835/C2 -Rev. 0, December, 1993) was written to "provide an acceptable methodology for establishing and operating an external dosimetry program." This IG outlines four essential elements of an acceptable external dosimetry program. These major elements were originally identified in the DOE/EH-0256T (Revision 1), *Radiological Control Manual*, a manual that establishes practices for the conduct of DOE radiological control activities. These elements are:

- Adequate staff who have been appropriately trained
- A technical basis document (relevant scientific information and rationale for elements contained in the external dosimetry program)
- Historical records of personnel dosimeter measurement results and dose assessments
- Internal audit programs (audit intervals not to exceed three years)

Personnel monitoring devices can be defined as devices designed to be worn or carried by an individual for the purpose of measuring the dose received. For the control of external radiation hazards, these devices include, but are not limited to, thermoluminescent dosimeters (TLD), film badges, and pocket ionization chambers.

Personnel monitoring programs are designed and conducted at nuclear facilities for several reasons. Among these are:

- Protecting the health of personnel
- Identifying poor work practices
- Detecting changes in radiological conditions
- Verifying the effectiveness of engineering and process controls
- Meeting ALARA considerations
- Demonstrating compliance with regulatory requirements
- Keeping adequate records



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From a regulatory standpoint, personnel monitoring is required under certain conditions, typically when a defined percentage of a dose limit is likely to be received. The requirements for DOE, taken from 10 CFR 835, follow. Section 835.402 addresses individual monitoring. The regulation requires personnel dosimetry be provided to and used by:

- Radiological workers, who, under typical conditions, are likely to receive one or more of the following:
 - An effective dose equivalent to the whole body of 0.1 rem (0.001 sievert [Sv]) or more in a year.
 - A shallow dose equivalent to the skin or to any extremity of 5 rem (0.05 Sv) or more in a year.
 - A lens of the eye dose equivalent of 1.5 rem (0.015 Sv) or more in a year.
 - A deep dose equivalent from external exposures to any organ or tissue other than the lens of the eye of 5 rem (0.05 Sv).
- Declared pregnant workers who are likely to receive, from external sources, a dose equivalent to the embryo/fetus in excess of 0.5 rem (the applicable limit in 835.206).
- Minors and members of the public likely to receive, in one year, from external sources, a dose in excess of 0.1 rem total effective dose equivalent (TEDE) (the applicable limits in 835.207 or 835.208, respectively).
- Individuals entering a high or very high radiation area.

Occupational exposure limits for general employees (DOE's new replacement term for occupational workers) are specified in Subpart C, Section 835.202.

Relevant limits are listed in the following table.

OCCUPATIONAL EXPOSURE LIMITS (10 CFR 835.202)	
Total Effective Dose Equivalent (TEDE)	5 rem (0.05 Sv)
Deep Dose Equivalent and Committed Dose Equivalent (Summation), to any organ or tissue	50 rem (0.5 Sv)
Eye Dose Equivalent	15 rem (0.15 Sv)
Shallow Dose Equivalent to the Skin or Extremities	50 rem (0.5 Sv)



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The DOE limits for planned special exposures are a separate issue and will not be discussed here.

The dose equivalent limit for the embryo/fetus (Section 835.206), covering the period from conception to birth, due to the occupational exposure of a declared pregnant worker, is 0.5 rem (0.005 Sv). The TEDE limit for minors (835.20) and members of the public (835.208) at a DOE site or facility is 0.1 rem (0.001 Sv). This limit also applies to visitors. In either case, personnel monitoring is required for these two groups of people at 50 mrem.

Subpart H of 10 CFR 835 (Sections 701 to 704) is devoted to recordkeeping requirements. In general, DOE indicates that records must be maintained to document compliance and retained until authorization for disposition by DOE is granted.

More specifically, records required to satisfy the final rule include: those related to compliance with ALARA provisions; results of individual external dose measurements; documentation of occupational exposures received during both current and prior years; data necessary to allow future verification or reassessment of recorded doses; results of surveys, measurements, and calculations used to determine individual occupational exposures; results of maintenance and calibration performed on personnel monitoring devices; training records; results of internal audits; and declarations of pregnancy.

Reports are required under Subpart I of 10 CFR 835. These include radiation exposure data for monitored individuals; records of exposure for terminating employees (at their request); an annual radiation dose report to each monitored individual; and required reports to DOE. Concerning the latter, any reports sent to DOE involving personnel exposure data must be sent to the individual as well.

Personnel dosimeter measurements are considered the preferred source of information for evaluating external doses (relative to workplace monitoring programs or other personnel monitoring programs). Examples of primary personnel monitoring devices (that is, those typically used for the measurement of the dose equivalent received) include: TLDs, film, and track-etch dosimeters. Audible-alarm dosimeters, electronic dosimeters, and pocket ionization chambers (direct and indirect reading) are examples of supplemental dosimetry (devices often worn with or located near the primary dosimeter). Be aware that some of these devices should not be used for the purpose of officially recording the dose to a worker.

Thermoluminescent Dosimeters

When certain materials (e.g., NaI, ZnS) are exposed to ionizing radiation, they absorb at least some of the radiation's energy and immediately release this energy as light. This process is known as scintillation. For each particle or photon of radiation interacting with the scintillating material, a flash of light is produced. The greater the energy absorbed by the material, the brighter the flash.



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With other materials (e.g., lithium fluoride [LiF], calcium sulfate [CaSO₄]), much of the absorbed energy is trapped rather than released immediately. Later, heating the material can cause this trapped energy to be released as light in a process called thermoluminescence.

Materials with this property are referred to as TL materials. The amount of energy absorbed by a material reflects the absorbed dose, and since the intensity of the emitted light is a measure of the absorbed energy, TL materials can function as integrating dosimeters.

Thermoluminescence is a two-stage process:

- The radiation energy is absorbed and trapped in the TL material.
- The trapped energy is released in the form of light when the TL material is heated.

A photomultiplier tube is used to convert the light pulses into an electronic signal which is subsequently displayed as a count rate. TLDs are typically used to detect beta, gamma, or neutron radiation.

Thermoluminescent materials are nonconducting crystalline solids (semiconductors or insulators). Many materials have the property of thermoluminescence (e.g., sodium chloride [NaCl] and diamonds), but only a few possess all the other characteristics desirable in a dosimeter. Commonly used TL materials in radiation dosimetry are LiF, lithium borate [Li₂ B₄ O₇], calcium fluoride [CaF₂], and CaSO₄. TL materials employed as dosimeters come in many forms: chips, rods, pellets, and powders. They can be encased in glass bulbs, covered with teflon, or deposited as a thin layer on a metal support.

In the workplace, TLDs are used to measure the external radiation dose received by radiation workers. TLDs can be used to assess the whole body dose or the dose to other parts of the body.

In the environment, TLDs are widely used to evaluate direct radiation (gammas and neutrons) emitted from a facility, gaseous releases from a facility (especially noble gases that are otherwise difficult to detect) and exposure rates associated with material deposited on the ground (from the air or water). For the most part, these TLDs primarily end up measuring natural background radiation. Unfortunately, background gamma exposure rates can vary greatly over short distances because of differences in geology. Furthermore, they can vary over time because of weather conditions. For example, heavy rain or snow can act to shield the TLDs from the terrestrial radiation (i.e., the potassium-40 [K-40], uranium [U] series, and thorium [Th] series) present in the soil.



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The various sites chosen for environmental TLDs should be physically similar and characteristic of the general area. Elevation (above sea level), as well as geology, can affect the exposure rates. Locations near large (especially dense) objects like buildings or rocks should be avoided. Such objects might be a source of radiation, or alternatively, shield the TLD from a source. Other areas to avoid include valleys or depressions where runoff can accumulate.

It is common to process environmental TLDs once a quarter. However, some facilities make more frequent measurements (e.g., monthly), while others do so less frequently (e.g., yearly).

The most widely employed TL materials for environmental measurements are LiF, CaF₂ (Dy) and CaSO₄ (Dy). The latter two are attractive for their sensitivity--something very desirable due to the low exposure rates typical of the environment. Since the energies associated with background gamma rays tend to be high, the over response of CaF₂ and CaSO₄ at low energies is not normally a problem. However, an accidental release from a facility might involve radionuclides emitting low energy gammas. If such a release is possible, and if calcium containing TLDs are used, some sort of compensating filtration should be employed to flatten the TLD's response at the low energies. Alternatively, the dosimeter should be able to evaluate the energy of the release and permit the application of appropriate correction factors.

Pocket Ionization Chambers

Direct-reading pocket dosimeters are small ionization chambers (typically the size of a pen) which contain a quartz fiber electroscope. They operate on the principle of ionization and are capable of responding to gamma and high energy beta radiation as well as neutrons if appropriately modified. Various ranges are available; however, 0 to 200 mR is probably the most common range utilized.

These devices contain fixed and movable quartz fibers that initially are similarly charged, forcing them to repel. As radiation enters the chamber and ionizes the air, charge is neutralized on the fibers and they move closer together. The degree of movement, and hence, the exposure is visualized by observing a hairpiece (movable fiber) through an eyepiece. The term "direct reading," therefore, comes from the fact that the individual can estimate the exposure at any time by holding the pocket dosimeter up to a light source and directly reading the value off a numerical scale. This constitutes an advantage over TLDs and allows the worker to keep track of his/her exposure. Disadvantages associated with these devices include their fragility (can go off scale if dropped) and expense. Pocket ion chambers are typically worn adjacent to whole body TLDs.



Problems/Issues

Some of the typical problems and relevant issues associated with the use of personnel monitoring devices include the following:

- The dosimeter may not respond to the various types of ionizing radiation encountered (i.e., beta particles, x-rays, gamma rays, and neutrons).
- Information as to the dose received is available only after the exposure (retrospective determination) rather than prior to the exposure (prospective determination).
- Pocket ionization chambers can "leak" current, resulting in erroneously high (or offscale) readings.
- Unreliability and improper use - Dosimeters, when they malfunction, can create a false sense of security for workers (this is especially true for audible-alarm dosimeters). Inappropriate use includes dropping the dosimeter or using it as a substitute for a survey meter. It may also include attaching the dosimeter to loose clothing and to neck chains, situations that can affect the dosimeter's response.
- Exposure to extraneous sources - Personnel dosimeters should not be exposed to elevated heat or sunlight, x-ray devices, or medical sources of radiation.
- Mixed radiation fields -The dosimeter may not properly respond to mixed radiation fields (e.g., gamma and neutron fields), resulting in an incorrect evaluation of the dose equivalent due to neutrons.
- Angular response -A commonly used practice in the field of radiation protection is to use one dosimeter as the measure of the whole-body dose. However, this assumes the worker will: (1) face the source of the radiation, and (2) "rigidly" attach the dosimeter to the anterior portion of the torso. This is often not the case. Angular response is an ongoing issue because of differing human body shapes and variation of dosimeter response with angle.
- Localized exposures and hot particles -Typically, only the exposure or dose to a small area on the anterior region of the body is evaluated as a measure of the whole-body dose. The possibility exists that other, more localized areas, could have been highly exposed. If an overexposure occurs, it may be necessary to reconstruct the exposure situation (never the preferred method). A prime example is the increasing occurrence and detection of so-called hot particles at nuclear facilities around the country. Hot particles are microscopic particles of high specific activity that



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can attach to clothing or exposed areas of the body. These hot particles are electrically charged and can, therefore, "hop" from one location to another, potentially resulting in highly localized, nonuniform beta/beta-gamma doses. In sum, the advent of more sensitive dosimetric equipment has created the ability to detect these particles, but at the same time, the appearance of hot particles has become a challenge from a personnel monitoring standpoint.

- Calibration - Dosimetric devices should be calibrated with traceable sources and secondary standards available through the National Institute of Standards and Technology (NIST).

To determine the whole-body dose, conventional guidance states that the dosimeter(s) should be placed on the trunk of the body and positioned so that the front of the badge holder is facing the source of the radiation. When the whole body dose is of interest (which assumes a fairly uniform exposure), monitoring devices should be placed between the neck and the waist.

The DOE IG on external dosimetry offers guidance on lens of the eye dosimetry. For uniform exposures, a measurement at the surface of the torso is sufficient for determining the dose equivalent. Nonuniform exposures, however, which include localized beams of radiation, x-ray machines, beta sources, penetrations, etc., would require the placement of a dosimeter on the side of the head or forehead, close to the eye.

For dosimetry related to the embryo/fetus, the IG entitled *Evaluation and Control of Fetal Exposure*, (G-10 CFR 835/C4 - Rev. 0), first suggests wearing a conventional whole-body personnel dosimeter between the neck and the waist as the basis of dose to the declared pregnant worker. Where exposures could approach 50 mrem in a month, the IG recommends an additional dosimeter--either a self-reading device or a second personnel dosimeter. This suggestion also holds for workers who are simply concerned over possible exposures to their unborn child. For exposures to localized sources of radiation, a supplemental dosimeter can be employed and should be placed closer to the waist or abdomen. The supplemental dosimeters are intended to track monthly exposures while, the primary dosimeter provides the dose of record.

Multiple dosimeters should be considered when the worker may receive an exposure from a source(s) located at other geometries relative to the front of the worker. The DOE *Radiological Control Manual* encourages the use of multiple dosimeters to assess whole body exposure when the radiation field varies by more than 50% over the area of the whole-body and the anticipated exposure is greater than 100 mrem (Chapter 5, Article 512). The DOE IG recommends placing multiple dosimeters at locations on the body where the highest dose equivalent would potentially be received. The head, chest, back, gonads, and top of arms and legs would be common candidates for dosimeters.

In the case of extremities, personnel dosimeters should be placed at the most exposed location on the extremities, (i.e., at or near the organ expected to receive the highest dose). These monitoring devices include ring badges, wrist badges, toe badges, and ankle badges.



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Personnel monitoring devices should always be worn when the worker is being (or is likely to be) exposed to radiation. Underexposures often result when the worker neglects to wear these devices. Therefore, for many facilities, it is a requirement to wear the appropriate dosimeters prior to the start of work.

DOE recommends that dosimeters not be issued to all individuals at their facilities unless a rationale for this action can be appropriately documented (For DOE, the documentation appears in a technical basis document.). Unnecessary issuance of dosimeters is discouraged, even in those cases where "concerned" individuals are involved because DOE believes information and training should come first. Once a dosimeter is appropriated to an individual, it should be worn only by the individual to whom it was issued. In the DOE system, dosimeters should neither be worn offsite nor worn to another site that issues its own personnel monitoring devices.

Personnel dosimeters should not be exposed to a radiation source when not on the worker. Storage of dosimeters in a high background area, for example, could result in reported overexposures.

The frequency of reading dosimeters varies with the type of dosimeter and site-specific procedures. They may be read once per quarter (i.e., TLDs) or as often as once per day (i.e., pocket dosimeters). With the recent advent of sophisticated computer-based personnel monitoring systems, it is now possible for nuclear facilities in this country to read their occupational TLDs up to several times each day as the workers pass through various plant access points.

NVLAP/DOELAP

Concerns about personnel dosimetry performance date back to the 1950s. Efforts to implement dosimetry performance standards have been attempted several times, but were always unsuccessful, primarily because only the performance of the dosimeter and not the dosimetry_processor was addressed.

Following recommendations put forth in 1973 by the Conference of Radiation Control Program Directors (CRCPD) during a workshop on personnel dosimetry evaluation and control, the National Bureau of Standards (NBS), as it was then known, prepared a performance criteria document. A draft standard based on this document was eventually developed in 1975 by the Health Physics Society (HPS) Standards committee for the American National Standards Institute (ANSI). This standard devoted itself to testing criteria for personnel dosimetry performance. Following a pilot study by the University of Michigan to evaluate the draft standard's workability and applicability, it was adopted by ANSI as ANSI N13.11-1983, *Personnel Dosimetry Performance - Criteria for Testing*. During this same time frame, discussions were also under way on the most desirable means



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to implement a national testing program. In 1980, these discussions led to the creation of the NBS National Voluntary Laboratory Accreditation Program (NVLAP). In 1982, the Nuclear Regulatory Commission (NRC) officially requested NVLAP to develop a laboratory accreditation program (LAP) for dosimetry processors, which would incorporate ANSI N13.11 as the performance criteria. This Dosimetry LAP officially took root in 1984.

NOTE: The first revision (September 1993) to ANSI N13.11 was recently developed by a HPS Standards Committee Working Group tasked by the ANSI with periodic reviews of this standard. As stated in the foreword to the standard, ANSI N13.11-1993 is applicable to the performance of all processors that provide dose or dose equivalent estimates for a permanent record of external personnel exposure. It specifies tests in nine different test categories (versus eight in the original standard). Furthermore, it corrects certain problem areas noted in the original performance tests, expands the scope of the testing and updates techniques and nomenclature. The testing program is considered to be more complex and more difficult in certain areas.

NVLAP is used by all NRC licensees (following rulemaking in February 1988) as the basis for accrediting their personnel dosimetry programs. DOE, after an independent evaluation of ANSI N13.11-1983, determined that it did not completely meet the needs of the DOE and its contractors. As a result, a distinct dosimetry testing program, the Department of Energy Laboratory Accreditation Program (DOELAP) was developed.

The DOELAP accreditation process is designed to assess whether specific criteria are met during an evaluation of a DOE facility's personnel dosimetry program. In other words, it is used to recognize a processor's competence, not dosimetry system performance. Competence, as used here, requires not only that all the items covered by the DOELAP criteria are met, but also that the processor demonstrates it has the staff, facilities and equipment, procedures, records and reports, and a quality assurance program. This process consists of several steps: 1) submission of an application; 2) payment of fees; 3) an onsite assessment that examines the technical adequacy, documentation and quality assurance associated with an application for accreditation; 4) proficiency testing; 5) resolution of any deficiencies in the program; 6) independent laboratory evaluations of the technical performance of dosimetry systems; and 7) administrative reviews.

Any processor that monitors individual exposures through the use of personnel radiation dosimeters and utilizes ionizing radiation categories specified in ANSI N13.11, is afforded the opportunity to attain accreditation.



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Several test categories, irradiation test ranges, and tolerance levels are included in ANSI N13.11 performance testing. (There are more, however, for DOELAP than NVLAP.) Examples of test categories include: 1) low and high energy photons; 2) beta particles; 3) moderated and filtered neutrons; and 4) mixture categories. These test categories, according to the standard, are most likely to significantly contribute to the dose equivalent received by radiation workers. Further refinements of these test categories will undoubtedly occur during future revisions of this ANSI standard.

A processor can choose one or more of these test categories--categories approximating the radiological conditions where they provide dosimetry services. The processor is not obligated, nor expected to, achieve accreditation in all available categories.

Currently, dosimeters used for determination of whole-body (deep) and skin (shallow) doses are included under the LAP (the dose equivalent to the lens of the eye is not determined). However, as was the case with the 1983 version, extremity dosimeters, pocket ionization chambers, and thermal neutron dosimeters are excluded from the accreditation process. Also excluded are practices utilized in an operational setting, such as the placement and attachment of dosimeters, multiple badging, and field calibrations. Additionally, area radiation monitors and dosimeters used for environmental applications are exempt from testing.

The primary goal of DOELAP remains the satisfactory performance of personnel dosimeters, and of equal importance, that of the processor. To that end, dosimeter technologies are evolving; criteria for angular dependence of dosimeter response and calculations of the lower limit of detection (LLD) for certain test categories have now appeared for the first time in the revision to ANSI N 13.11, and a future revision of this standard is being discussed.

Radiation Monitoring Systems

Radiation monitoring systems consist of several different types. Included in this category are criticality monitors, area radiation monitors (ARMs), process monitors, and airborne monitors.

The purpose of nuclear criticality accident alarms and alarm systems is to alert personnel to promptly evacuate the area to reduce the risk of exposure to radiation. Generally, the nuclear criticality accident alarm system is meant to prevent large exposures to many people. Criticality alarm systems are generally composed of neutron or gamma radiation detectors and annunciation (signal) equipment. In addition, administrative procedures are needed to ensure that the equipment is maintained and properly calibrated.

A nuclear criticality accident occurs without advance warning. There are no discernible indications that the accident is about to happen. Therefore, nuclear criticality accident alarm systems are after-the-fact alarms. Generally, the alarm will sound about half a second after the criticality has occurred.



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ANSI/ANS 8.3-1986, *Criticality Accident Alarm System*, addresses not only the need for alarm systems, but also describes the characteristics of alarm signals, dependability, testing procedures, and emergency planning. The specifications for alarm signals include recommended sound pressure levels and activation mechanisms that do not depend on human action. The standard also provides guidance on the criteria for system design.

ARMs are utilized to control radiation exposures in a workplace setting. Emphasis is typically placed on the detection of gamma radiation intensities throughout the facility. To satisfy that objective, ARMs are either wall-mounted or operated as a free-standing unit in areas requiring monitoring. These devices tend to be fairly rugged and versatile, yet compact and lightweight. G-M or ionization chamber detectors are typically used. Depending on the detector, energy compensation is provided to allow a flat roentgen response versus gamma energy. Radiation levels ranging from 0.01 mR/hr up to 10,000 R/hr are typical. ARMs are designed to provide normal/fail indicators for safe operation; remote indicators are available that include meter, audible, and visual alarms. High radiation alarms and alarms designed to alert the worker that an alert level has been exceeded can be set over the entire meter range. Audible alarms often consist of a horn; visual alarms employ a light or beacon that may flash on and off depending on the design.

From a regulatory perspective, the use of stationary (area) or portable radiation instrumentation for the purpose of measuring ambient radiation dose rates is required under 10 CFR 835.403(b). The DOE *Radiological Control Manual* (Article 553) offers several recommendations regarding these monitors.

Process radiation monitors are designed to detect concentrations of liquid and gaseous radioactivity in work areas, stacks, ducts, laboratories, etc. A variety of these systems exist and are routinely used as indicators of both normal and abnormal system operating conditions. They may also provide an estimate of the quantity of radioactivity released to the environment.

DOE EH/0173T, *Environmental Regulatory Guide*, addresses liquid and gaseous effluent monitoring in Chapters 2 and 3, respectively. Both chapters are intended to assist each DOE-controlled facility in meeting the requirements of DOE Order 5400.1, *General Environmental Protection Program Requirements*, and DOE Order 5400.5, *Radiation Protection of the Public and the Environment*.

Airborne monitors are used at DOE facilities to detect the presence of airborne radioactivity. continuous air monitors (CAMs) provide one example of a device designed to continuously sample and measure the air for radioactivity. These devices provide real-time monitoring capability and have the potential to alert the worker to unexpected increases in airborne radioactivity levels.



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At DOE facilities, the emphasis in the occupational setting is often devoted to detecting the presence of alpha-emitting transuranics such as plutonium, americium, etc. Beta CAMs are also used. If a preset exposure level is exceeded, possibly due to an unplanned release, modern CAMs are designed to activate an alarm system with the intent of reducing occupational exposures. CAMs should be designed to respond in the shortest possible time and at the lowest detectable level of radioactivity, keeping in mind the need to reduce, and preferably avoid, spurious alarms. Alarm capability and adequate sensitivity are requirements mandated in 10 CFR 835.403(a)(3).



Scenario 1

Based on the information above, what reasons can you supply as to why the G-M detector read zero counts/minute? List three mistakes the RCT made in responding to the researcher's call.

This image shows a blank sheet of white paper with horizontal ruling lines. The lines are evenly spaced and run across the width of the page. There are no margins, text, or other markings on the paper.



What possible reasons can you cite for the failure of the employee to egress the building? What concerns are raised in this scenario?

[illegible]



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Scenario 1, Solution

(Any reasonable paraphrase of the following is acceptable.)

The detector would not indicate a reading if the batteries were dead or extremely weak. In addition, it is possible that if the radiation levels were extremely high, the instrument would saturate and read "0" counts per minute due to excessive dead time (the inability of the instrument to handle high radiation levels.)

The technician should not have entered the room so quickly, considering the nature of the situation, (i.e., the potential presence of a high activity gamma source). In addition, the RCT apparently picked up an old radiation detector which it had not been used in some time. The capabilities of the instrument to do the job then becomes suspect. The calibration status of this G-M detector appears to be suspect as well; 10 CFR 835.401(c)(1) states that instruments used for monitoring shall be calibrated at least once per year. Furthermore, the instrument should not have been turned on after the RCT entered the room. This is a poor health physics practice and could have had serious repercussions from a personnel safety perspective.

In short, appropriate responses in this scenario regarding the instrumentation should have included choosing an appropriate instrument, performing a visual examination and proper instrument checks (battery, high voltage, source check, etc.), and assessing the calibration status. In addition, following good health physics practices (such as exposure-reducing controls) and exercising proper judgment should be fundamental components of the technician's response in this and similar situations.

Scenario 2, Solution

(Any reasonable paraphrase of the following is acceptable.)

It is conceivable that the employee did not hear the criticality alarms/monitors or observe any visible indicators that an alarm had sounded. The employee was found in an area with potentially high noise levels from the operation of the air-handling units. The inability to hear a criticality accident alarm has occurred at DOE facilities where high-noise levels were present or when the systems did not provide full detection and alarm coverage. Shielding effects in buildings have sometimes been the reason for lack of coverage or the inability to hear the alarms. There have also been instances where visual indicators were not present in particular rooms or areas of a building.

ANSI/ANS 8.3, *Criticality Accident Alarm System*, contains relevant sections pertaining to this scenario. Section 4.4.1 requires quarterly checks of audible alarms in areas that may require personnel evacuation. Alarms are required to be of sufficient volume and coverage to be heard in all areas requiring evacuation. Section 4.4.11 recommends visual signals in high background noise levels. Detectors are required by Section 5.8 to be located and spaced to avoid the effect of shielding by equipment or materials.



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The overriding concern in this scenario is personnel safety. Criticality accidents can result in lethal doses to an individual. For this reason, criticality safety is of extreme importance at those DOE facilities handling, processing, storing, etc., fissionable materials. Every attempt, therefore, should be made to eliminate the direct causes of criticality accident alarm system deficiencies. These deficiencies have been documented by DOE and encompass six areas (listed in generally decreasing order of occurrence): personnel error, design problems, equipment/material problems, management problems, procedural issues, and external influences.



4. SUGGESTED ADDITIONAL READINGS AND/OR COURSES

Readings

- Argonne National Laboratory. (1988). *Department of Energy Operational Health Physics Training* (ANL-88-26). Argonne, IL: Author.
- Gollnick, Daniel A. (1991). *Basic Radiation Protection Technology* (2nd ed.). Pacific Radiation Corporation: Altadena, CA.

Courses

- *Nuclear Physics/Radiation Monitoring* -- DOE.
- DOE/EH-0450 (Revision 0), *Radiological Assessors Training (for Auditors and Inspectors) - Fundamental Radiological Control*, sponsored by the Office of Defense Programs, DOE.
- *Applied Health Physics* -- Oak Ridge Institute for Science and Education..
- *Health Physics for the Industrial Hygienist* -- Oak Ridge Institute for Science and Education.
- *Radiological Worker Training* -- DOE-EH.
- *Radiological Control Technician Training* -- DOE-EH.
- *Safe Use of Radionuclides* -- Oak Ridge Institute for Science and Education.
- *Radiation Protection General Technical Base Qualification Standard Training* -- GTS Duratek.